

Close Binary System GO Cyg

B. Ulaş^a, B. Kalomeni^{a,b}, V. Keskin^a, O. Köse^a, K. Yakut^{a,c,*}

^a*Department of Astronomy and Space Sciences, University of Ege, 35100,
Bornova-İzmir, Turkey*

^b*Department of Physics, İzmir Institute of Technology, Turkey*

^c*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3
0HA, UK*

Abstract

In this study, we present long term photometric variations of the close binary system GO Cyg. Modelling of the system shows that the primary is filling Roche lobe and the secondary of the system is almost filling its Roche lobe. The physical parameters of the system are $M_1 = 3.0 \pm 0.2 M_\odot$, $M_2 = 1.3 \pm 0.1 M_\odot$, $R_1 = 2.50 \pm 0.12 R_\odot$, $R_2 = 1.75 \pm 0.09 R_\odot$, $L_1 = 64 \pm 9 L_\odot$, $L_2 = 4.9 \pm 0.7 L_\odot$, and $a = 5.5 \pm 0.3 R_\odot$. Our results show that GO Cyg is the most massive system near contact binary (NCB). Analysis of times of the minima shows a sinusoidal variation with a period of 92.3 ± 0.5 years due to a third body whose mass is less than $2.3 M_\odot$. Finally a period variation rate of -1.4×10^{-9} d/yr has been determined using all available light curves.

Keywords: stars: binaries: eclipsing — stars: binaries: close — stars: binaries: general — stars: fundamental parameters — stars: low-mass

1. Introduction

Studies of the evolution of late-type close binary systems reveal that the evolution of detached, semi-detached and contact systems are closely related (Yakut & Eggleton 2005, Eggleton 2010 and reference therein). The more massive star in a detached binary system fills its Roche lobe first because it has shorter evolutionary timescale before its companion. The system is semi-detached binary. In addition to nuclear evolution and mass loss, mass transfer has a crucial role in driving a binary towards a contact phase of evolution.

*Visiting astronomer during the summer of 2011

The observations of detached, contact and semi-detached binaries are crucial to our further understanding of the evolution of close binary systems.

We therefore, include GO Cyg (HD 196628, GSC 02694-00550, $V=8^m.47$, A0V) into our close binary stars observation programme (see Ulaş et al. 2011, Köse et al. 2011). The system is a β -Lyr type (short period $0^d.71$) binary system and observations of the binary cover eighty years. Following its discovery by Schneller (1928) the system has been extensively studied by many authors. (Payne-Gaposchkin, 1935; Pierce, 1939 and Popper, 1957). Ovenden (1954); Mannino (1963); Rovithis et al. (1990); Sezer et al. (1993); Jassur (1997); Rovithis-Livanou et al. (1997); Edalati & Atighi (1997); Oh et al (2000), and Zabihinpoor et al. (2006) studied the system photometrically. Using different methods in analysis most studies agree with the primary filling its Roche lobe. Asymmetry in the secondary minimum have been discussed in previous studies (e.g. Edalati & Atighi 1997, Zabihinpoor et al. 2006). Pearce (1933) found the mass function and mass ratio of 0.85 for GO Cyg. Later studies have reported higher mass ratios. Pribulla et al. (2009) examined the binary and classified it as a member of a group called *difficult binary stars*. In this group accurate radial velocities are not available. Pribulla et al. (2009) concluded that the temperature difference between the components makes the system a difficult candidate in determination of the ideal broadening function. A velocity value of $v \approx 35$ km/s for a third body was given in Pribulla et al. (2009).

Period variation of GO Cyg has been studied by many investigators. Period increase was discussed in a number of studies (e.g. Sezer et al. 1985, Rovithis et al. 1997, Edalati & Atighi 1997, Zabihinpoor et al. 2006). Jones et al. (1994) reported a sinusoidal variation superimposed on a parabolic trend. Elkhateeb (2005) noted a period increase of $dP/dt = 1.28 \times 10^{-7}$ which is close to that of Oh et al.'s (2000) value of 1.51×10^{-7} . Hall & Louth (1990) discussed a magnetic cycle by studying the period decrease between the year 1934 and 1984. Chochol et al. (2006) represented the $O-C$ curve by a sinusoidal fit by using the Cracow database and their data. A third body with an orbital period of 90 years and a mass of $0.62M_{\odot}$ has been proposed.

In the following sections, we present our new observations of GO Cyg. We performed photometric analysis, period variations and compare our results with its previously published works. All the available light curves were collected from the literature and studied for various physical processes (e.g. magnetic activity, mass transfer, third light) and their variations. The $O-C$ variation with recently obtained times of minima revealed the discrepancy

between the results of the light curve solution and period study of earlier studies. In this study, therefore, we investigate different possibilities that cause period variation in order to reveal the most accurate structure and behavior of the components. The physical parameters of the system are given with a discussion on the evolutionary status of the binary.

2. New Observations

The light variation and minima times of GO Cyg obtained in the Bessel B , V , and R bands in 16 nights between June – August 2007 and one night in April 2011. The observations carried out at TÜBİTAK National Observatory (TUG) and Ege University Observatory with the 40cm telescope using an Apogee CCD U47. Comparison and check stars are selected as GSC 02694-00280 and GSC 02694-00733, respectively. The total number of the points obtained during the observations are 3715 in B , 3726 in V , and 3698 in R band. IRAF (DIGIPHOT/APPHOT) packages are used in data reduction. Standard deviations of the data are estimated as $0^m.04$, $0^m.017$, and $0^m.015$ for B , V , and R bands, respectively.

In Fig. 1 we show the B , V , and R light curves of GO Cyg. In this study, we do not find the apparent asymmetry in 0.6-0.7 orbital phase previously reported by Edalati & Atighi (1997) and Zabihinpoor et al. (2006). In data our reduction and analysis, we used the linear ephemeris described by Sezer et al. (1993).

3. Eclipse Timings and Period Study

Cester et al. (1979) reported an orbital increase of $Q = 0.7 \times 10^{-10}$ based on seven nights observational data obtained between 1972-1975. Sezer et al. (1985) also reported an increase with a Q value of 1.13×10^{-10} days. Hall & Louth (1990) consider the $O - C$ curve and split it in three region. The first and the third region of the curve showed sudden variation. Therefore the authors analysed these regions under linear assumption while the second part was presented by a quadratic fit with a period increase of $Q = 1.28 \times 10^{-10}$. The authors concluded that this behavior of the $O - C$ curve can be attributed to a magnetic cycle. Jones et al. (1994) showed that the residuals of the parabolic fit show a sine-like variation with a period of 38.9 years. A period increase was also discussed by Rovithis-Livaniou et al. (1997). A period with $Q = 1.6 \times 10^{-10}$ was noted by Edalati & Atighi (1997). Oh et al.

(2000) also represented the $O - C$ curve by an upward parabola with $Q = 1.47 \times 10^{-10}$. Elkhateeb (2005) found that the period is increasing with a value of $Q = 1.26 \times 10^{-10}$. The parabolic and third order polynomial fits were compared by Zabihinpoor et al. (2006). The authors give the quadratic term as 0.935×10^{-10} . Zabihinpoor et al. (2006) also discussed the inconsistency between geometric configuration and period variation rate. Recently, Chochol et al. (2006) suggested the light time effect for the period variation. The authors discussed that in a binary system where the primary fills its Roche lobe and loses mass a decrease in orbital period can be expected.

Recently we obtained two times of minima $24\ 54318.54864 \pm 0.00013$. and $24\ 55676.56220 \pm 0.00016$. The times of minima obtained in this study show that the $O - C$ curve changes shape from early-assumed upward parabola to a sinusoidal variation that supports the previous discussion about a third body in the system. The period variation is studied using a total of 194 data points obtained by photometric/CCD observations. The times of minima are obtained from the literature (Kreiner et al., 2001 and Erkan et al., 2010) and those yielded by this study. The weighted least-squares method is used in order to determine the orbital elements of the third body. Sinusoidal variation in the O-C curve, where both the primary and the secondary minima follow the same trend suggests a light-time effect because of the presence of a third component that can be represented by following formula (Irwin 1959, Kalomeni et al. 2007):

$$\begin{aligned} MinI &= T_o + P_o E + \\ &+ \frac{a_{12} \sin i'}{c} \left[\frac{1 - e'^2}{1 + e' \cos v'} (v' + \omega') + e' \sin \omega' \right] \end{aligned} \quad (1)$$

where T_o is the starting epoch for the primary minimum, E is the integer eclipse cycle number, P_o is the orbital period of the eclipsing binary a_{12} , i' , e' , and ω' are the semi-major axis, inclination, eccentricity, and the longitude of the periastron of eclipsing binary about the third body, and v' denotes the true anomaly of the position of the center of mass. Time of periastron passage T' and orbital period P' are the unknown parameters in Eq. (1).

Our result from our analysis are shown in Fig. 2. Fig. 2a shows the consistency between the observational and model prediction in the assumption of a third body. Fig. 2b shows the residuals from a Sinusoidal variation. The orbital elements of a third component are listed in Table 2. It can be

clearly seen from the figure that any investigation of any detailed variation in $(\Delta T)_{II}$ points makes no sense. We have also investigated orbital period variation of the system with a different method from the $O - C$ analysis. We have re-analysed the light curves from the available eighty years and we discussed further in Section 5 below. We conclude that if the $O - C$ variation shows a downward parabola its period that is too long to determine from available times of minima.

4. Light Curve Solution

The light curve of the system has been analysed by numerous researchers. Ovenden (1954) obtained two-colour light curve and solved them by using Russell’s method. The author assumed that the primary dominates observed light. This results in a reflection effect that makes difficult to identify the secondary in the spectrum. Asymmetry between maxima discussed as an intrinsic variation. Mannino (1963) solved the photoelectric B and V light curves of the system with the Russell–Merill method. Rovithis et al. (1990) analysed the light curves and estimated the geometric elements by using frequency domain techniques. The authors reported no difference between the level of maxima. The BV light curve combined with Holmgren’s radial velocity curve was solved by Sezer et al. (1993) by using Wilson–Devinney (WD) method. The result indicated a semi-detached configuration where the primary is filling its Roche lobe. A standard iterative optimization technique was used by Jassur (1997) to solve the UBV light curves. Rovithis-Livanou et al. (1997) determined the absolute parameters and the geometrical elements by applying the Wood’s model. Edalati & Atighi (1997) compared some parameters of their solution with previous works and confirmed that the system’s geometrical configuration is a reverse Algol. Oh et al. (2000) discussed that the system is at poor thermal contact phase of the thermal relaxation oscillation. Recently, Zabihinpoor et al. (2006) analyzed the light curve and suggested new observations to uncover the discrepancy between the suggested geometric shape and the orbital period variation.

The shapes of the radial velocity curves of the system are controversial and no reliable spectroscopic mass ratio exist in the literature. In this study, therefore, we started to the solution by searching the appropriate photometric mass ratio. q values between 0.25 and 0.65 are investigated on the V light curve by increasing the value by 0.05. We reached the minimum residual when $q = 0.45$ which is then taken as an initial value for our simultane-

ous solution. The uncertainties of the spectral types also required to search for a suitable temperature for the primary component using the light curve. $T_h=10350$ K turned out to be a suitable mean temperature of the hot component and has been used in other studies. Simultaneous solutions obtained with PHOEBE (Prša & Zwitter 2005), which uses the WD code (Wilson & Devinney 1971), was applied to our observations (476 points in B and V , and 474 in R). The gravity darkening coefficients g_1 and g_2 are obtained from von Zeipel (1924) and Lucy (1967). The albedos A_1 and A_2 are adopted from Rucinski (1969). The logarithmic limb-darkening law is used with coefficients adopted from van Hamme (1993) for a solar composition (Table 2). The adjustable parameters are orbital inclination i , temperature of secondary component T_2 , surface potential of secondary component Ω_2 , luminosity L_1 , and mass ratio q . The analysis results are summarized in Table 2. The computed light curves are shown with solid lines in Fig. 1.

All available light curves of the system between 1936–2007 are also collected from the literature and analysed separately (Table 3). These light curves are solved by using the initial values that are determined in this study. In addition, light contribution of the third body is set as a fixed parameter since no variation is expected in a period of eighty years. The results are shown in Fig. 3 and listed in Table 4. All available data are provided in Table 5.

Some light curves (LC8, LC12, LC15) show slight asymmetry in the secondary minimum while it is not detected in the others (LC3, LC7, LC14). In this study we also investigate any evidence of a magnetic activity as it was discussed in earlier studies (Hall & Louth 1990). Either physical structure of the stars or the shape of the light curves did not let us to analyse the curves with spotted model assumption. Some light curves (LC8, LC15), however, can be represented theoretically by a hot surface on the cooler companion. The presence of a hot region, that may be attributed to a mass transfer other than a magnetic activity, could not be proved with the long-term data.

5. Discussion and Conclusion

Long term photometric light and period variation of the close binary system GO Cyg are studied in detail. The physical parameters we have determined and listed in Table 6. Because of poor quality data in the previous studies the $O - C$ curve was inferred to be parabolic one. In this study with our data we show that the system has a third body with a 92.3 years orbital

period. Since the primary component filled its Roche lobe we searched for a clue for the mass transfer by a technique other than the $O - C$ analysis. Separate solutions of six available light curves starting from 1950 to present indicate a period decrease. The period change variation vs. years shows a downward parabola. This can be considered as a mass transfer from the more massive companion to the less massive one. This solution yields the amount of the period decrease as -1.4×10^{-9} d/yr with a mass transfer rate of 1.5×10^{-9} M_{\odot} /yr. In addition, the period of this parabolic variation is too long to detect in the $O - C$ curve constructed with the available data.

The system has been studied spectroscopically but no accurate radial velocity study of it is available in the literature. In systems like GO Cyg the luminous primary star makes it difficult to treat the system as a double-lined binary. Determination of the physical parameters requires the knowledge of accurate mass ratio and the mass of the primary component. The best result obtained by a q -search technique in the light curve analysis. In what follows solution to allowed the mass ratio to vary allowing with other parameters when the solve for an orbital the light curves. Our solutions all have similar results for all nine light curves. Our results are given in Table 2-3. Spectral studies of NCB systems (e.g. GO Cyg) are quite difficult because of their nature. The mass of the primary, therefore, estimated according to their colors, spectral types *etc.* In this study, we used recently published astrophysical data of well known stars (e.g., Torres et al., 2010, Yakut & Eggleton, 2005, Drilling & Landolt 2000) to estimate the primary's (the massive and luminous one) mass. By studying stars with similar luminosities and spectral types, the mass of the primary is assumed to be $3.0 M_{\odot}$. This is also consistent with the values given in the literature. The physical parameters of the system is given in Table 6, the results are consistent with the similar systems on the $M - R$, $M - L$ and the Hertzsprung–Russell diagrams given by Yakut & Eggleton (2005). Our results shows that GO Cyg has the most massive components among the known NCB systems. We collected physical parameters of the NCB systems whose primary components are relatively massive (Table 7). Mass-luminosity diagram of binaries listed in Table 7 is shown in Fig 4. The locations of GO Cyg A and B in the $M - L$ diagram are consistent with the other NCB systems.

Observational results of semi-detached systems show that while in some cases the primary component fills its Roche lobe (GO Cyg) in other cases the secondary fills its Roche lobe (V836 Cyg, Yakut et al., 2005). These differences are a sign for the evolutionary stage of the binary system (for

details we refer Yakut & Eggleton 2005, Eggleton 2006, Eggleton 2010). The orbital, geometrical, and physical parameters of GO Cyg presented in this study indicate the Roche lobe filling star is the primary (the massive and the hotter one). We show that the primary may even transfer mass with at a low rate. Contrary to the very low mass stars, mass loss rate due to the magnetic stellar winds can be expected since the convective layer is small in the systems with intermediate/low mass components (e.g. GO Cyg). The results indicate the system GO Cyg evolves under the proximity effect, low rate mass transfer between the components ($\dot{M} = 1.5 \times 10^{-9} M_{\odot}/\text{yr}$) and the third body can also remove angular momentum from the binary orbit.

Acknowledgments

This study was supported by the Turkish Scientific and Research Council (TÜBİTAK 109T047 and 111T270) and Ege University Research Fund. KY+VK acknowledges support by the Turkish Academy of Sciences (TÜBA). We thank to an anonymous referee, J.J. Eldridge and E.R. Pekünlü for their valuable comments and suggestions.

References

- Cester B., Giuricin G., Mardirossian F., Mezzetti M., 1979, *Acta Astron.*, 29, 433
- Chochol D., et al., 2006, *Ap&SS*, 304, 93
- Drilling, J. S., & Landolt, A. U. 2000, *Allen's Astrophysical Quantities*, 381
- Edalati M. T. & Atighi M., 1997, *Ap&SS*, 253, 107
- Eggleton, P. 2006, *Evolutionary Processes in Binary and Multiple Stars*, Cambridge Astrophysics Series No. 40
- Eggleton P. P., 2010, *NewAR*, 54, 45
- Elkhateeb M. M., 2005, *JKAS*, 38, 13
- Erdem, A., Zola, S., Winiarski, M. 2011, *NewA*, 16, 6
- Erkan N., Erdem A., Akın T., Aliçavuş F., Soyduğan F., 2010, *IBVS*, 5924, 1

Hall D. S., Louth H., 1990, JApA, 11, 271

Irwin J. B., 1959, AJ, 64, 149

Jassur D. M. Z., 1997, Ap&SS, 249, 111

Jones R. A., Snyder L., Frey G., Dalmau F. J., Aloy J., Bonvehi L., 1994, IAPPP, 54, 34

Kalomeni B., Yakut K., Keskin V., Değirmenci Ö. L., Ulaş B., Köse O., 2007, AJ, 134, 642

Köse O., Kalomeni B., Keskin V., Ulaş B., Yakut K., 2011, AN, 332, 626

Kreiner J. M., Kim C.-H., Nha I.-S., 2001, aocd.book

Lee J. W., Kim C.-H., Kim S.-L., Lee C.-U., Han W., Koch R. H., 2008, PASP, 120, 720

Lee J. W., Kim S.-L., Lee C.-U., Kim H.-I., Park J.-H., Park S.-R., Koch R. H., 2009, PASP, 121, 104

Liau S. P., 1935, POLyo, 1

Lucy, L. B., 1967, Z. Astrophys., 65, 89

Mannino G., 1963, MmSAI, 34, 191

Oh K.-D., Kang Y. W., Ra K. S., Park H. S., 2000, Ap&SS, 271, 303

Oprescu G., Dumitrescu A., Suran M. D., Rovithis P., Rovithis-Livaniou H., 1996, RoAJ, 6, 119

Ovenden M. W., 1954, MNRAS, 114, 569

Payne-Gaposchkin C., 1935, BHarO, 898, 3

Pearce J. A., 1933, JRASC, 27, 62

Pierce N. L., 1939, AJ, 48, 113

Pols O. R., Tout C. A., Eggleton P. P., Han Z., 1995, MNRAS, 274, 964

Popper D. M., 1957, APJS, 3, 107

Pribulla T., et al., 2009, AJ, 137, 3655

Prša, A., Zwitter, T., 2005, ApJ, 628, 426

Rovithis P., Rovithis-Livaniou H., Niarchos P. G., 1990, A&AS, 83, 41

Rovithis-Livaniou H., Rovithis P., Oprescu G., Dumitrescu A., Suran M. D., 1997, A&A, 327, 1017

Rucinski, S. M., 1969, Acta Astron., 19, 245

Schneller, H., 1928, AN, 235, 85

Sezer C., Gülmen O., Güdür N., 1985, IBVS, 2743, 1

Sezer C., Gülmen O., Güdür N., 1993, Ap&SS, 203, 121

Torres G., Andersen J., Giménez A., 2010, A&ARv, 18, 67

Ulas B., Kalomeni B., Keskin V., Kose O., Yakut K., 2011, arXiv, arXiv:1107.0277

van Hamme, W., 1993, AJ, 106, 2096

von Zeipel, H., 1924, MNRAS, 84, 665

Vukasović M., 1997, IAPPP, 67, 11

Wilson, R.E., Devinney, E.J., 1971, ApJ, 166, 605

Wronka M. D., Gold C., Sowell J. R., Williamon R. M., 2010, AJ, 139, 1486

Yakut K., Eggleton P. P., 2005, ApJ, 629, 1055

Yakut K., Ulaş B., Kalomeni B., Gülmen Ö., 2005, MNRAS, 363, 1272

Zabihinpoor S. M., Dariush A., Riazi N., 2006, Ap&SS, 302, 27

Zhang L.-Y., 2010, PASP, 122, 309

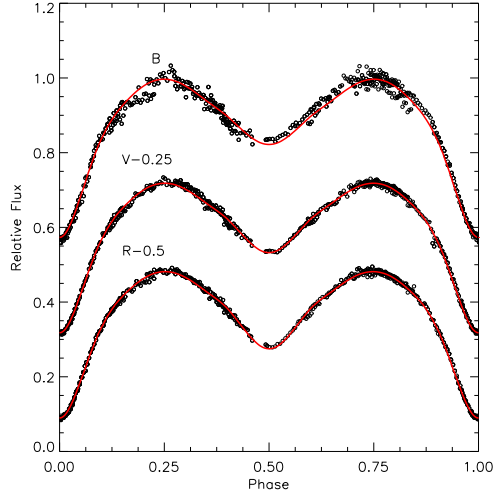


Figure 1: The observed and the computed (solid line) light curves of the system GO Cyg. The light curves in V and R bands are moved by a value of 0.25 and 0.5, respectively, for the sake of comparison.

Table 1: Results of the period analysis and the orbital elements of the third body. The standard errors, 1σ , are given in parentheses.

Parameter	Unit	Value
T_o	[HJD]	2433930.4283(7)
P_o	[day]	0.717764585(15)
P'	[year]	92.3(5)
T'	[HJD]	2414756(300)
e'		0.46(1)
ω'	[$^\circ$]	20.3 (2.2)
$a_{12} \sin i'$	[AU]	4.57 (4)
$f(m)$	[M_\odot]	0.0112(5)
$m_{3;i'=20^\circ}$	[M_\odot]	2.30
$m_{3;i'=90^\circ}$	[M_\odot]	0.65

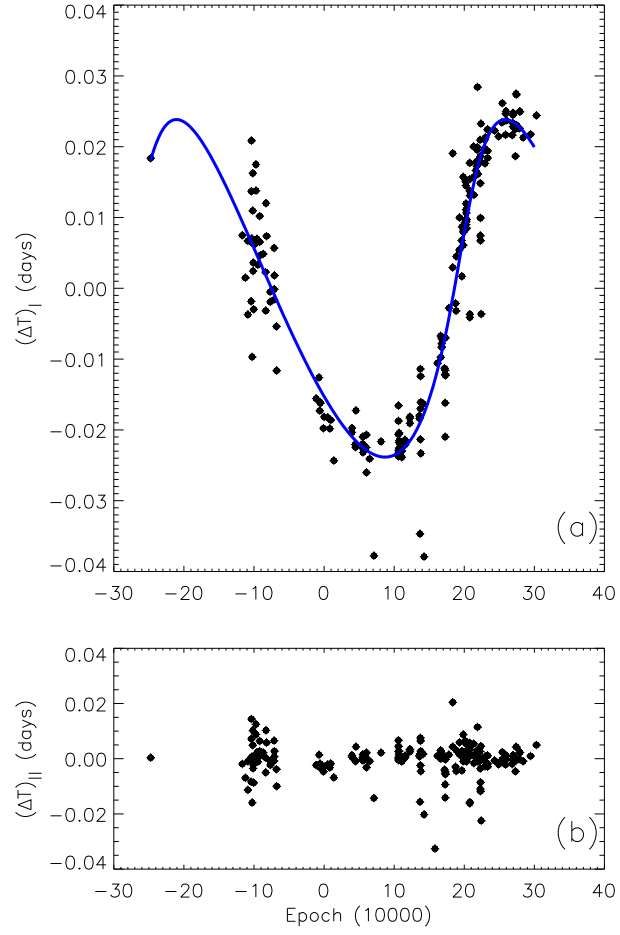


Figure 2: (a) Residuals for the times of minimum light of GO Cyg. The solid line is obtained with the assumption of sine-like variation. (b) The difference between the observations and the computed sinusoidal curve.

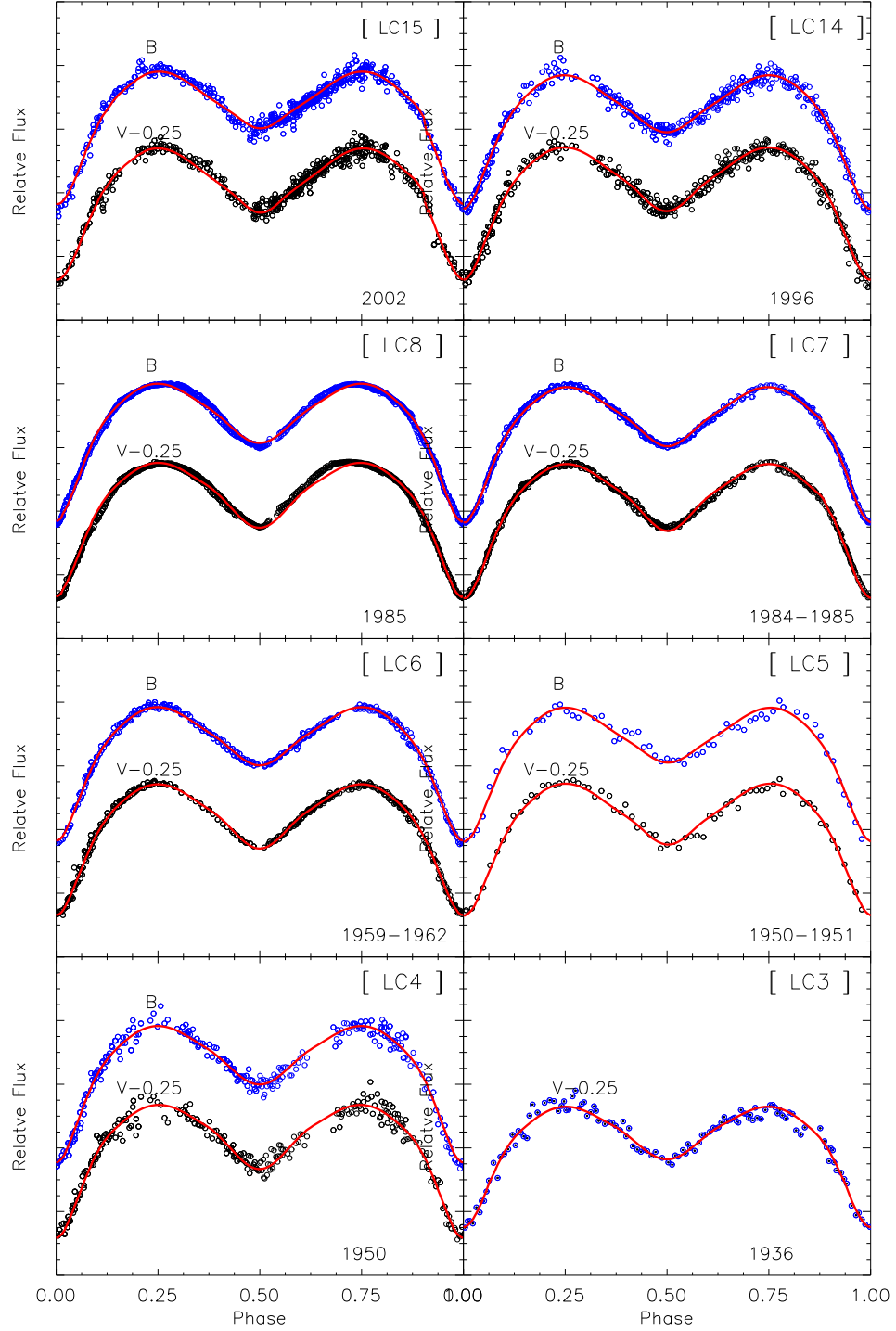


Figure 3: All available light curves (phase-intensity) of the system between 1936 and 2002. The theoretical curves (solid lines) are drawn using the results given in Table 6. At the right bottom of each panel observation years are given.

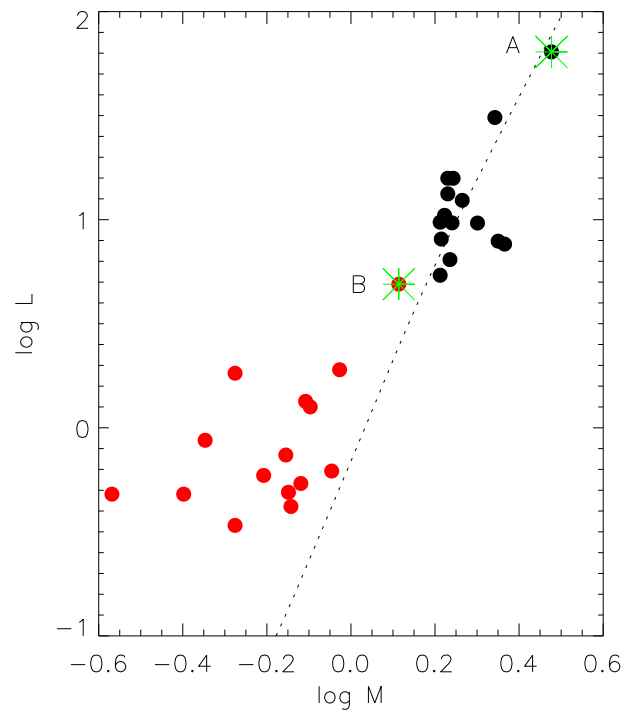


Figure 4: Plot of the $M - L$ plane of the some NCB systems. The ZAMS line is taken from Pols et al. (1995).

Table 2: The photometric elements and their formal 1σ errors of GO Cyg. See text for details.

Parameter	Value
Geometric parameters:	
i ($^\circ$)	75.67(3)
Ω_1	2.735
Ω_2	2.686(4)
q	0.428(9)
Fractional radius of primary	0.4542(2)
Fractional radius of secondary	0.3189(12)
Radiative parameters:	
T_1 (K)	10350
T_2 (K)	6490(90)
Albedo A_1	1.0
Albedo A_2	0.760
Gravity brightening g_1	1.0
Gravity brightening g_2	0.32
Limb darkening x_1, x_2	
x_1B	0.693
x_2B	0.812
x_1V	0.593
x_2V	0.721
x_1R	0.484
x_2R	0.628
Luminosity ratio: $\frac{L_1}{L_1+L_2+l_3}$ (%)	
B	94(5)
V	90(4)
R	87(4)
Luminosity ratio: $\frac{l_3}{L_1+L_2+l_3}$ (%)	
B	0.39
V	0.37
R	0.38

Table 3: Available light curves of GO Cyg that are collected from the literature. JD* refers to the time interval of data taken. In data availability column (Data), "Yes" and "No" is shortened by the letter Y and N, respectively. Photoelectric observations are abbreviated by "pe" while "pg" and "ccd" refers to the photographic and CCD observations. Light curves are LC1: Payne-Gaposchkin (1935), LC2: Liao (1935), LC3: Pierce (1939), LC4: Popper (1957), LC5: Ovenden (1954), LC6: Mannino (1963), LC7: Sezer et al. (1993), LC8: Rovithis et al. (1990), LC9: Oprescu et al. (1996), LC10: Jassur (1997), LC11: Rovithis-Livaniou et al. (1997), LC12: Edalati and Atighi (1997), LC13: Vukasović 1997, LC14: Oh et al. (2000), LC15: Zabihinpoor et al. (2006), LC16: This study.

ID	Year	JD*(2400000+)	Filters	Type	Comparison(s)	N _{points}	Data
LC1	1934		blue, red	pg	BD +36 4150 BD +34 4098 BD +35 4197		N
LC2	1935						N
LC3	1936		V	vis	BD +35 4188	122	Y
LC4	1950	33478.8-33498.0	B,V	pe	HD 196771	B:261, V:261	Y
LC5	1950-51		B,V	pe	BD +35 4197 BD +34 4098	B:64, V:68	Y
LC6	1959-62	36782.4-37910.5	B, V	pe	BD +35 4197 BD +34 4098	B:333, V:353	Y
LC7	1984-85	45866.4-46348.3	B,V	pe	HD 197 292 HD 197 346	B:416, V:414	Y
LC8	1985	46264.3-46329.4	B,V	pe	BD +35 4180 BD +34 4098	B:631, V:633	Y
LC9	1989-92		B,V	pe	BD +35 4197 BD +34 4098		N
LC10	1992		U,B,V	pe	BD +35 4180 BD +34 4098		N
LC11	1993-94		B,V	pe	BD +35 4197 BD +34 4098		N
LC12	1995		U,B,V	pe	BD +35 4180 BD +34 4098		N
LC13	1996		U,B,V	pe	SAO 70314		N
LC14	1996	50366.0-50436.0	B,V	pe	BD +35 4197 BD +34 4098	B:398, V:397	Y
LC15	2002		B,V	pe	HD 197292 HD 197346	B:545, V:521	Y
LC16	2007	54361.5-54321.6	B, V, R	ccd	GSC 02694-00280 GSC 02694-00733	B:3711, V:3722, R:3694	Y

Table 4: The photometric parameters and 1σ errors obtained from the solution of all available light curves. See text for details.

Parameter	LC3	LC4	LC5	LC6	LC7
i ($^\circ$)	75.2(1.5)	77.1(3)	73.42(1.03)	75.57(8)	76.61(3)
q	0.371(26)	0.435(5)	0.443(17)	0.425(2)	0.457(1)
T_1 (K)	10350	10350	10350	10350	10350
T_2 (K)	6111(240)	6667(64)	6516(144)	6721(30)	6743(18)
Ω_1	2.616	2.764	2.749	2.729	2.786
Ω_2	2.603(65)	2.722(18)	2.627(18)	2.662(3)	2.702(2)
$(\frac{L_1}{L_1+L_2})_B$	-	0.934(47)	0.932(101)	0.927(18)	0.913(13)
V	0.938(124)	0.896(53)	0.895(122)	0.892(21)	0.877(14)
R	-	-	-	-	-
r_1	0.4676(65)	0.4512(11)	0.4528(34)	0.4549(3)	0.4490(2)
r_2	0.2965(268)	0.3184(46)	0.3420(151)	0.3238(16)	0.3352(13)
	LC8	LC14	LC15	LC16	
i ($^\circ$)	77.02(2)	74.2(1)	74.5(1)	75.67(3)	
q	0.424(2)	0.457(2)	0.461(2)	0.428(9)	
T_1 (K)	10350	10350	10350	10350	
T_2 (K)	6688(23)	6651(50)	6709(35)	6478(262)	
Ω_1	2.713	2.785	2.804	2.735	
Ω_2	2.711(6)	2.674(3)	2.612(3)	2.686(4)	
$(\frac{L_1}{L_1+L_2})_B$	0.913(13)	0.933(15)	0.922(32)	0.941(59)	
V	0.906(16)	0.885(36)	0.862(30)	0.908(48)	
R	-	-	-	0.875(46)	
r_1	0.4567(4)	0.4490(3)	0.4472(3)	0.4542(2)	
r_2	0.3110(21)	0.3405(15)	0.3680(22)	0.3189(12)	

Table 5: Available light curves data. Phases are given for the light curves LC3, LC5, and LC15 since JDs are not provided. All data for 9 data sets can be found electronically at CDS.

Data Set	Filter	JD/Phase	Magnitude
LC6	B	2436782.3973	0.156
LC6	B	2436782.4034	0.158
LC6	B	2436782.4117	0.173
LC6	B	2436782.4184	0.184
LC6	B	2436782.4198	0.187
\vdots	\vdots	\vdots	\vdots

Table 6: Absolute parameters of GO Cyg. The standard errors 1σ in the last digit are given in parentheses.

Parameter	Unit	Pr.	Sec.
Mass (M)	M_{\odot}	3.0(2)	1.3(1)
Radius (R)	R_{\odot}	2.50(12)	1.75(9)
Temperature (T_{eff})	K	10350	6490
Luminosity (L)	L_{\odot}	64(9)	4.9(7)
Absolute bolometric magnitude (M_b)	mag	0.23	3.03
Period change rate (\dot{P})	d/yr	-1.4×10^{-9}	
Mass transfer ratio (\dot{M})	M_{\odot}/yr	1.5×10^{-9}	
Seperation between stars (a)	R_{\odot}	5.5(3)	

Table 7: Physical parameters of some well known massive ($M > 1.6 M_{\odot}$) NCB systems. The data is taken from Yakut & Eggleton (2005) except RZ Dra (Erdem et al., 2011), RU UMi (Lee et al., 2008), GW Gem (Lee et al., 2009), EE Aqr (Wronka et al. 2010), KQ Gem (Zhang 2010).

Name	Sp.T	P(d)	M_1	M_2	$\log L_1$	$\log L_2$
RZ Dra	A5	0.5509	1.63	0.70	0.988	-0.131
RT Scl	F0	0.5116	1.63	0.71	0.733	-0.310
RV Crv	F3	0.7473	1.64	0.45	0.907	-0.060
AG Vir	A8	0.6427	1.67	0.53	1.021	0.262
DO Cas	A7	0.6847	1.70	0.53	1.124	-0.469
KQ Gem	F5	0.4080	1.70	0.40	1.199	-0.319
SW Lyn	F2	0.6441	1.72	0.90	0.808	-0.208
GW Gem	A7	0.6594	1.74	0.80	0.985	0.100
FO Vir	A8	0.7756	1.75	0.27	1.199	-0.319
YY Cet	A8	0.7905	1.84	0.94	1.093	0.279
RS Ind	A9	0.6241	2.00	0.62	0.984	-0.229
V836 Cyg	B9.5	0.6534	2.20	0.78	1.491	0.127
EE Aqr	A9.5	0.5090	2.24	0.72	0.897	-0.378
RU UMi	A9	0.5249	2.32	0.76	0.883	-0.268
GO Cyg	B8	0.7178	3.00	1.30	1.806	0.690